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Jet Inlet Efficiency

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Interns investigated improvements for the BVM jet inlet used by the RWWV flight team.

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1 SUMMARY

The purpose of the investigation in this report was to find a means for improving airflow into a BVM super bandit jet intake, in order to improve thrust efficiency. The two solutions we focused on testing were boundary layer diverters and vortex generators. A series of tests were run trying out a variety of different vortex generators and boundary layer diverters configurations. In the end a combination of the two had the best results. That final configuration had a square leading edge boundary layer diverter with a height of 6mm at the front of the inlet, followed by 5 co-rotating vortex generators with a height of half an inch just inside the intake. These test items could be permanently applied to the jet for an improvement to the thrust efficiency, but even better results could be found if further tests expanded upon our own.

2 INTRODUCTION

The objective of the investigation detailed in this report was the improvement of thrust efficiency in the BVM super bandit jet in use by the AFRL RWWV flight team. The jet engine could provide 50 pounds of thrust uninstalled, however once installed in the airframe, that very same engine could only provide 34 pounds of thrust. That is roughly a 30% loss of thrust. The exhaust of the jet is a straight tube which has minimal chance of inducing losses, however the dual intake consists of multiple curves and is also flush with the surface of the jet, therein lays our problem.

The intake being flush with the surface of the jet is a problem because it allows the ingestion of the boundary layer that has formed along the length of the jet prior to the intake. The jet fuselage extends about 34 inches in front of the intake, which should induce a boundary layer of approximately 3/10th of an inch. On an intake that is only a few inches wide that can be a substantial amount of the air flow entering the duct at less than free stream velocity, causing a loss of thrust efficiency.

The curvature in the intake ducting is an issue because it causes an adverse pressure gradient that leads to flow separation in intake. This in turn leads to pressure distortion on the face of the compressor, reducing efficiency.

After investigating many other jet intakes on full scale fighter jets, one design feature stands out as being on the BVM jet. That design feature is call a boundary layer diverter, and as the name implies it works by offsetting the intake from the fuselage and diverting the slow flowing boundary layer air around the intake. Below in figure 1 are two examples of the boundary layer diverters (BLDs) on a F-15 and F-4. Our BLDs design was based largely on the F-4 BLD because we were instructed to avoid changing the airframe if possible.

Figure 1: Boundary Layer Diverters of F-15 and F-4

Further research was required in order to overcome the issue of flow separation, but we came upon one possible solution in the form of vortex generators. Vortex generators work by creating small wing tip vortices that will cause small amounts of turbulence that

will mix fast moving free stream air with the slow moving air along the surface (boundary layer). This in effect breaks down the boundary layer as well delays flow separation. Prior research on the application of vortex generators in inlets was limited but I did find the some help in the 1996 AIAA report “Vortex generator installation studies on steady state and dynamic inlet distortion” by Anderson and Gibb. It was had prior testing data on a variety of VG configurations in a duct. Another helpful source was an 1974 ASME publication by Y.Senoo & M. Nishi titled “Improvement of the Performance of Conical Diffusers by Vortex Generators”. This report had more general information different types of vortex generators. In addition to these reports I used a collection of Ken Blackburn’s notes on vortex generations.

In the following report we will detail the processes we followed to manufacture the test items, the order of our testing operations, the results of the tests, and the detailed discussion on what the results mean and how they can be best applied to solve the issue of thrust lost due to the intake duct inefficiencies.

3 METHODS, ASSUMPTIONS, AND PROCEDURES

Machining, Molding, Manufacturing

Assumptions/Notes:

During the Machining, Molding and Manufacturing process, there are a few assumptions that can be made about the refining tools. Their use was smoothing pieces and helping to remove excess material. The specific tools used are listed below.

- Dremel – tool was used to remove majority of excess material in a timely manner.
- Power sander – tool was used to sand down surfaces and edges or reshape pieces evenly.

Processes:

1. Female Molding of fuselage from fuselage (Plaster)

Procedure –

- Create a dam around desired area
  - Using heated clay, pack on a thick layer around the edge of the desired area and build upwards to a substantial height. The height must be even and go above the height of the intake.
  - Verify that the clay is smooth, even, and well connected to the jet to ensure it will last the entire process.
  - Ensure that there are no holes in the clay dam.
  - The clay hardens quickly.
- Wax the surface and place the film
  - Clean the desired area of any clay or debris.
  - Put wax onto fabric or a brush and evenly lay two or three coats.
  - Lay down a coat of PVA Release Film.
- Mix and lay down plaster
  - Place desired amount of plaster mixture (Plaster of Paris) into a container or bucket.
  - Mix in the water to desired consistency.
  - Quickly pour the mixture over the desired area and spread to ensure that the mixture lies evenly.
    - Note: Plaster hardens in an extremely short time period; only lay plaster that can easily be manipulated by hand, once the mixture is too solid it can no longer be used
  - Allow the plaster to sit over the area for approximately 24 hours or overnight.

- One the mold has set, remove it from the surface and place in an oven until all of the moisture is gone.

- Use
  - This mold can now be used to create a male mold that will be an exact replica of the original piece (fuselage).

2. Male Mold of fuselage (Fiberglass)

Procedure –

- Lay material
  - Place the female mold firmly and flatly on the ground.
  - Lay three layers of wax and three layers of PVA Film Release. Allow the Film Release to dry before laying down each layer.
  - Gather three layers of smooth fiberglass fabric (in sheets large enough to cover entire piece) and multipurpose adhesive.
  - Put short quick sprays of the multipurpose adhesive over the surface and place a layer of the smooth fiberglass fabric over the female mold. Ensure that the fabric is even and hugs the structure of the mold. Repeat this process for the next two layers.
  - Once all of the fabric has been placed, mix the epoxy for spreading.
  - Mix the epoxy resin and then the epoxy cure with a 4:1 ratio for 1-2minutes.
  - Evenly pour epoxy over the layers of fabric until fully saturated.
- Seal and set structure
  - Place a sheet of liner over the saturated fabric.
  - Lay down plastic sheeting that is double the size of the mold covered in fabric in order to fully envelope the mold.
  - Line half of the sheet (in an open square form) with clay tape and insert a lacerated hose for even suction over the fabric and mold.
  - Fold the other half of the sheet over the mold and connect to clay tape to create an air tight sealed bag with a hose leading to the outside pump.
  - Once the seal is created, turn on the connected pump to remove all air from the bag that has been created.
    - Ensure that as air is removed, the bag fits the form of the desired mold as closely as possible.
  - Allow the mold to sit under these conditions for at least 12 hours (overnight).
- Separate and refine piece
  - Break the seal over the piece and remove all fabric and plastic sheeting.
  - Separate the female mold from the male mold by removing excess material and placing wedges between the pieces.

- Once separated, refine the pieces by smoothing edges, smoothing the surface, and removing any excess material that still remains.

- Use
  - This mold is the exact shape of the fuselage of the jet and therefore can operate as a stand in for testing, modeling, prototyping other processes without using the actual equipment.
  - This process was repeated to take a fiberglass male mold from the later created fiberglass female mold.

3. Female Mold of fuselage from male mold (Fiberglass)

Procedure –

- Lay material
  - Use the male mold of the fuselage as a template. Lay the mold flatly on a covered surface.
  - Wax the surface of the male mold two times and place three coats of PVA Film Release on the male mold. Allow each layer of Film Release to dry before adding the next.
  - Create a mix of epoxy by mixing epoxy resin followed by epoxy cure in a 4:1 ratio.
  - Lay a layer of rough fiberglass fabric in small patches over the male mold.
  - Apply the epoxy mixture and as the epoxy saturates the fabric, help form the fabric to the shape of the mold with hands.
  - Repeat the process for two or three more layers laying down the fabric in patches and applying the epoxy.
  - Ensure that the fabric is saturated with the epoxy.
- Let structure set
  - Allow the uncovered structure to sit to ensure that the structure sets and the fabric comes together.
  - The structure should sit at least 12 hours (overnight).
- Separate and refine piece
  - Once solid, separate the new fiberglass female mold from the male mold by removing excess material and placing wedges between the pieces.
  - After separation, make final adjustments to refine the piece by smoothing edges, the surface, and removing excess material still present.
- Use
  - This mold is used to create future male molds of the original front fuselage without taking the mold directly from the jet fuselage repeatedly.

4. Vortex Generator (Aluminum/Galvanized Steel)

Procedure –

- Outline design
    - Desired designs were created in inventor and made into a one dimensional flat design for sheet metal cut outs.
    - Print these designs and outline them directly onto the sheet metal desired.
    - Draw the lines of where the metal is designed to bend to form the final shape.
- Cut and refine piece
    - Using a ban saw, cut out the outlined shapes when using aluminum.
    - When using the galvanized steel using a flat blade machine that operates by making one stroke at a time with a blade to make straight slices through the material.
    - With either machine, make the desired cuts to the outline.
    - Refine the pieces cut out by sanding down the edges in order to have them the desired shape.
- Shape the piece
    - Once the flat pieces are in the desired shape, you must bend the edges as desired.
    - Use the lines drawn on each pieces as crease indicators as the mark at which to bend the piece.
    - Bend each area as closely to 90 degree angle as possible.
- Use
    - Multiple sets were created

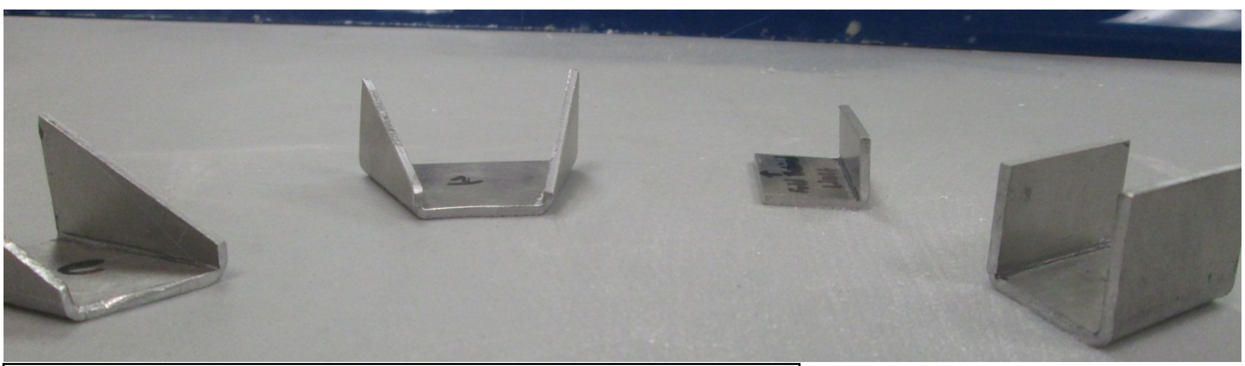


Figure 2: Example of batch 1 vortex generators

        - Original prototypes were made, on aluminum, and were larger than desired.
        - Thinner metal and smaller scale designs were then made on aluminum, but the aluminum could not hold the strain of the 90 degree bend and the pieces became broken.
        - Final pieces were made on galvanized steel at the correct scale size and could be used successfully.
    - These pieces can be placed on or around the fuselage or duct as desired to control air flow.

5. Boundary Layer Diverter (Carbon Fiber/Foam)

Procedure –

- Obtain materials
- Shape materials
- Attach pieces

Pre-Testing

Assumptions/Notes:

There were few assumptions made during the pre-testing process. It was found that unraveled yarn would be used because it matched the requirement needed for testing. Those requirements included to be easily moved by any change in air flow and therefore, they needed to be thin and light.

Process:

1. Duct Flow Visualization

Procedure –

- Thin yarn and place within duct
    - Take yarn and unravel into individual strands.
    - Cut small pieces of these strands and tape them, in a row, onto a section of the duct.
    - Place rows of string flowing down the duct.
- Connect testing apparatus
    - Connect the jet ducts to a damageable plastic piece of connector. Use painters tape for the original connection (to prevent damage to the ducts) and use duct tape to reinforce the connection.
    - Connect the open end of the plastic piece to a piece of aluminum semi-rigid ducting with more duct tape.
    - Connect the open end of the aluminum ducting to the leaf blower fan with tape to cover any possible holes between the two.
- Run test
    - Turn on the leaf blower to begin the suction through the duct.
- Use
    - Test was only run once.
    - Watching the behavior of the stings inside the duct during suction can identify qualities of the air flow. The strings in a specific row will flow according to the shape of the duct if air is flowing steadily, however, the

stings will stand up and away from the structure if there is any separation or disturbance in the air flow. The test helps identify positions of flow separation.

Wind Tunnel Testing

Assumptions/Notes:

During testing within the wind tunnel it is found that there are a few conditions and specifics that need to be taken note of.

Some of the main concepts that need to be taken note of are the different set up types of the testing apparatus. Below there is a list of different ways in which the apparatus was set up. Note that static shows conditions that never changed through testing, and the other two conditions show two different types of baseline set-ups.

- Static Testing Conditions
  - Jet fuselage with canopy attached by tape and ducts placed inside
  - Aluminum semi-rigid ducting attached to rear of ducts leading to leaf blower fan (suction)
  - Jet fuselage placed in middle of wind tunnel stream secured to metal beams
- Jet's Base Conditions
  - All static testing conditions in place
  - No alterations or solutions attached to jet
- Dirty vs. Clean testing condition
  - All static conditions present with only difference in the inlet to duct connection
  - Dirty: jet assembled as intended by manufacturer
  - Clean: inlet to duct connection secured with gaps between the two covered by strip of tape

There are also specific things that must be noted about the many readings taken and recorded through our testing. These are listed below.

- Pressure measured in mmHg
- Velocity measured in m/s
- Measurements taken through Pitot tube

Through testing there were specific observations that were made. These observations are listed to explain changes in testing procedure and style that are noted in from process to process.

- During "Inlet Mapping" testing it was found that measurements are closest to ideal/real conditions with the leaf blower setting on high

- During “Boundary Layer Definition (HotWire)” it was determined that measurements closest to ideal/real occurred with the Wind Tunnel on high

Processes:

1. Pitot Tube Calibration

Procedure –

- Pitot Tube placement
    - Place Pitot Tube in mount at the mouth of the Wind Tunnel pointed into the tunnel (towards the incoming wind stream)
- Wind Tunnel settings array
    - Capture velocity readings from each voltage level produced by the wind tunnel (levels 1-10).
    - The velocity will be a mean velocity taken from 10 averages.
- Use
    - Performed under the jet’s dirty base condition.
    - This procedure is used to calibrate the Pitot Tube to the wind tunnel’s voltage versus velocity output.

2. Inlet Mapping

Procedure –

- Pitot Tube placement
    - Mount the Pitot Tube near the inlet of the jet. Have the Pitot tube facing into the stream of wind.
- Pitot Tube movement
    - Take an array of data from five specific locations. The locations include the middle of the inlet, the upper right corner, upper left corner, lower right corner, and lower left corner. The formation should form an X shape.
    - Move from one location to the other taking readings of velocity (mean velocity taken from 10 averages) and pressure (mean pressure taken from 10 averages) under specific conditions.
- Use
    - Performed under the jet’s dirty base condition.
    - At each location four settings of conditions were tested
        - Leaf Blower on Low, Wind Tunnel on Low
        - Leaf Blower on Low, Wind Tunnel on High
        - Leaf Blower on High, Wind Tunnel on Low
        - Leaf Blower on High, Wind Tunnel on High
    - This test is used to map out the behavior of the jet’s inlet.

3. Boundary Layer Definition (Pitot Tube)

Procedure –

- Pitot Tube placement
    - Place the Pitot tube at the middle of the inlet's outer edge.
- Specific testing condition
    - Run the leaf blower on high and collect the velocity and pressure readings (means of 10 averages).
- Pitot Tube movement
    - Under these conditions take the readings by moving from the edge of the inlet inward by increments of .25inches or so. Move towards the surface of the fuselage from the edge of the inlet until there is no room to move any closer.
- Use
    - Performed under jet's dirty base condition.
    - Run through only one time.
    - This test is used to define the thickness of the boundary layer before the inlet.

4. Boundary Layer Definition (HotWire)

Procedure –

5. Flow Proficiency Testing

Procedure –

- Pitot Tube placement
    - Place the Pitot tube in a small hole in the aluminum ducting.
    - Position the tube to be near the inner wall of the right half duct.
- Use
    - Base Test
        - Performed under jet's dirty base conditions.
        - Collect the pressure and velocity (means taken from 10 averages) from high and low Wind Tunnel speeds.
    - Vortex Generator V.G. Orientations
        - Performed under jet's dirty testing conditions
        - For each orientation tested take the pressure and velocity (means of 10 averages) with the Wind Tunnel on low and high settings.

- Orientations Tested:

  - Orientation One: 1 counter-rotational V.G. and 2 single V.G.'s (1 inch from inlet).

Figure 3: VG orientation 1

  - Orientation Two: 2 co-rotational V.G.'s and 1 single V.G. (1 inch from inlet)

Figure 4: VG orientation 2

Figure 5: VG orientation 3

- Orientation Three: Orientation 2 farther from inlet (2.5 inches from inlet).

- Orientation Four: 1 single V.G. (1.5 inches within duct on the rounded surface).

Figure 6: VG orientation 4

- Orientation Five: Orientation two within duct (1.5 inches within duct on the flat surface).

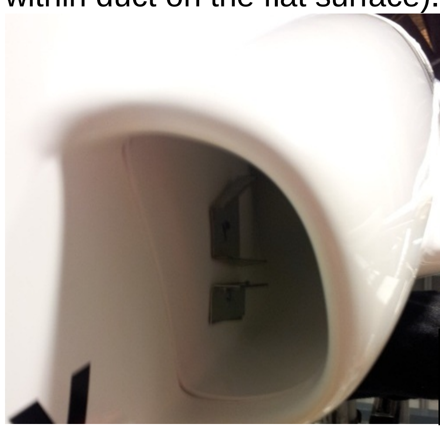


Figure 7: VG orientation 5

- Base Condition Alignment
  - Base measurements of pressure and velocity (means taken of 30 averages) to find best jet conditions
  - Performed under Jet's Dirty and Clean testing conditions.
- Primary/Main Testing
  - Performed Under Jet's Dirty and Clean testing conditions
  - For each configuration tested the pressure and velocity (means taken of 30 averages) is recorded with the Wind Tunnel on high.
  - Configurations Tested

- Configuration A (Tested under Clean and Dirty)
  - Vortex Generator Orientation 2 (1 inch from the inlet)
- Configuration B (Tested under Dirty)
  - Boundary Layer Diverter Set-up 1 (directly in front of inlet)
    - Foam base height: right and left inlet – 7.5mm
    - Fiberglass frame shape: right and left -parallel
    - Foam base shape: right and left -triangular
- Configuration C (Tested under Dirty)
  - Boundary Layer Diverter Set-Up 2
    - Foam base height: right-10.5mm, left-7.5mm
    - Foam base shape: right-curved, left-triangular
    - Fiberglass frame shape: both – parallel
- Configuration D (Tested under Dirty)
  - Vortex Generator Orientation 2 (1 inches from inlet)
  - 1 counter-rotational V.G. (1.5 inches inside duct on curved surface)
- Configuration E (Tested under Dirty and Clean)
  - Vortex Generator Orientation 2 (1 inch inside duct on the flat surface)
- Configuration F
  - Boundary Layer Diverter Set-Up 3
    - Foam base height: right-6mm, left-7.5mm
    - Foam base shape: both - triangular
    - Fiberglass frame shape: both - parallel
- Configuration G
  - Boundary Layer Diverter Set-Up 4
    - Foam base height: right-6mm, left-7.5mm
    - Foam base shape: both - triangular
    - Fiberglass frame shape: right-square, left parallel
- Configuration H
  - Boundary Layer Diverter Set-Up 5 with Vortex Generator Orientation 2 (on edge of duct)
    - BLD Foam base height: right-6mm, left-7.5mm
    - BLD Foam base shape: both - triangular
    - BLD Fiberglass frame shape: both - square
- Configuration I
  - Boundary Layer Diverter Set-Up 5 with Modified Vortex Generator Orientation
    - BLD Foam base height: right-6mm, left-7.5mm
    - BLD Foam base shape: both - triangular
    - BLD Fiberglass frame shape: both – square
    - V.G.’s – 2 co-rotational V.G.’s(on edge of duct)
- Configuration J
  - Boundary Layer Diverter Set-Up 5

      - Foam Base height: right-6mm, left-7.5mm
      - Foam base shape: both - triangular
      - Fiberglass frame shape: both - square

Additional Data Collection/REEF Testing

Assumptions/Notes:

The geometry of these aluminum ducts tested were made to resemble original geometry of aluminum duct used to do all previous wind tunnel testing. This was done so the assumption that the same ducting conditions were present. Many of the compared measurements are listed below.

- Original aluminum duct diameter – 4 inches
- New aluminum ducting diameter (both) – 4 inches
- Original duct assumed extended length – 8 feet
- New Aluminum ducting extended length – 7ft. 5inches

There are a few notes to be taken about the readings that were taken during this experiment. These notes are found below.

- Pressure readings from Pitot tubes are means taken from 30 averages
- Pressure from Pitot tubes all taken in mmH_2O

There are a few specific observations that are good to be noted during testing. Any relevant observations for the additional testing are listed below.

- Diameter of the aluminum ducting tested for the additional testing decreases when the duct is condensed and increases as duct is extended.

Processes:

1. Static Pressure Collection

Procedure –

- Assemble Testing Apparatus
  - Secure one opening of aluminum duct to the fan of a leaf blower with duct tape. Stretch this first piece of duct to its full length.
  - Attach a second, identical, aluminum duct that to the open end of the first with duct tape. Leave this duct mostly condensed.
  - Secure the leaf blower and ducting so that they do not move once the leaf blower is turned on.
- Pitot Tube Placement

- Place one Pitot tube at the connecting point of the first aluminum duct and the second aluminum duct by placing a small hole in the aluminum and sliding the Pitot tube into the center, facing the open end of the apparatus.
    - Place the second Pitot tube at the opening of the second aluminum duct by placing a small hole in the aluminum and sliding the tube to the middle of the duct facing out towards the duct's opening.
    - Secure the first Pitot tube so that it does not move for the entire process and secure the second Pitot tube so that it is stable enough for testing, but mobile.
- Run Wind and Collect Data
    - Run the leaf blower on the settings high and on low.
    - On each setting take readings from both locations on the apparatus (middle and free stream).
    - The readings will be of the dynamic pressure, stagnation pressure delta, and static pressure.
- Use
    - Test was run at interval lengths of the second duct
        - Length 1 – 1' 14", atmospheric pressure was 101403 Pascal's
        - Length 2 – 2' 9", atmospheric pressure was 101413 Pascal's
        - Length 3 – 4' 3", atmospheric pressure was 101420 Pascal's
        - Length 4 – 5' 9", atmospheric pressure was 101413 Pascal's
        - Length 5 – 7' 2", atmospheric pressure was 101392 Pascal's
    - This test was done to relate duct length to pressure readings and review the leaf blower's efficiency

4 RESULTS AND DISCUSSION

The first test ran was an attempt to map the pressure and velocity distribution across the inlet face. Both pressure and velocity were recorded at 5 locations in approximately an "X" pattern depicted below in figure 8.

Table 1

Tunnel Speed Low; Blower Low					
Position	1	2	3	4	5
Avg. Vel	10.07	9.54	9.53	9.65	9.88
Avg Pressure	6.2	5.57	5.55	5.71	5.99
Tunnel Speed High; Blower Low					
Position	1	2	3	4	5
Avg. Vel	16.42	16.9	17.17	16.91	16.17
Avg Pressure	16.53	17.51	18	17.51	16.07
Tunnel Speed High; Blower High					
Position	1	2	3	4	5
Avg. Vel	17.12	17.38	16.67	17.3	16.86
Avg Pressure	17.98	18.51	16.96	18.36	17.39
Tunnel Speed Low; Blower High					
Position	1	2	3	4	5
Avg. Vel	10.73	9.99	8.39	10.09	9.88
Avg Pressure	7.05	6.11	4.32	6.24	6.97

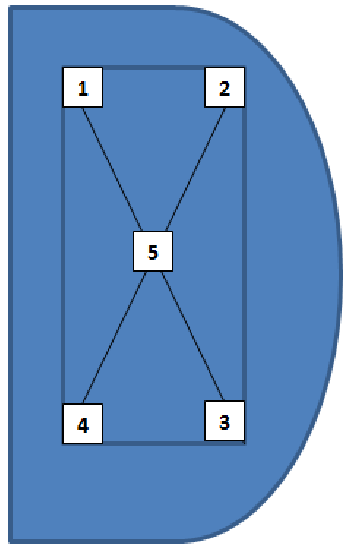


Figure 8: Inlet Mapping

Based on these results it was choose to conduct the remainder of the tests with the leaf blower only set to its highest setting, due to that being closer to the actual jet, though still notably weaker.

As mentioned in the procedures, the next objective was to define the height of the boundary layer created by the airframe leading up to the intake. This was done in two ways, firstly with the 8th of an inch pitot tube used for all the other tests and later with a hot wire for greater accuracy. The results of both are shown below.

Table 2 : Pitot Boundary Layer Test				
	Low Wind Speed		High Wind Speed	
Distance	Velocity	Pressure	Velocity	Pressure
30	10.63	6.89	16.93	17.59
25	10.57	6.81	17.33	18.45
20	10.87	7.24	17.03	17.7
15	10.8	7.13	17.04	17.81
10	10.82	7.17	17.13	17.95
5	10.94	7.3	16.73	17.16
3.5	10.83	7.2	16.71	17.13
2	9.06	5.03	13.64	11.35

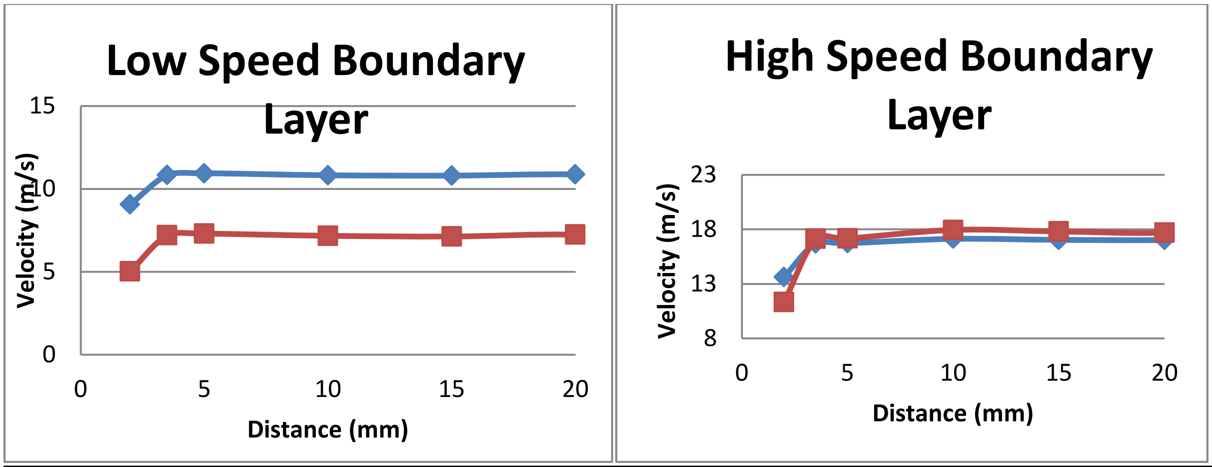


Figure 9 : Pitot boundary layer test showing a boundary layer height of less than 3.5mm

Based on the pitot tube results of less than 3.5mm we realized that the boundary layer was significantly smaller than our approximation of between 3/10th and half an inch (7.62-12.7mm). This was significant because the designs of the VG's and BLDs were based on the ½ inch boundary layer assumption. These affects will be discussed in greater detail later in the report.

Due to the unexpected results of the pitot boundary layer test it was deemed necessary to conduct another boundary layer test with a greater degree of accuracy than the pitot tube could provide, this lead to the use of a hot wire. The hot wire can very accurately determine local velocities. For the hot wire test, the velocity was measured in 1mm increments, resulting in the more complete visual of the velocity profile on the following page. Upon inspection of the hot wire data the boundary layer appears to be closer to 6mm from the surface of the jet. This value has some uncertainties due to the end of a boundary layer being defined as the point with 99% of the free stream velocity however it can be seen in the figure below the free stream is not necessarily uniform.

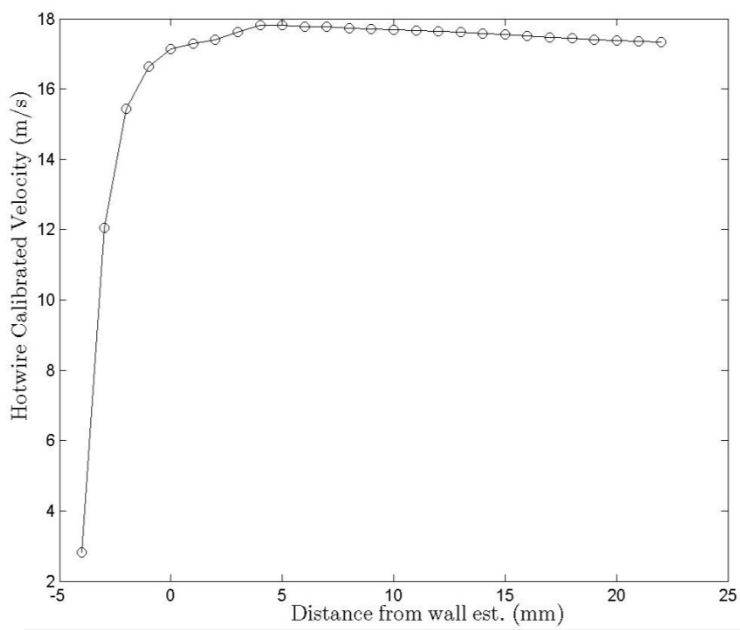


Figure 10: Velocity profile found using hot wire test, showing a boundary layer of approx. 6mm

The first modifications tested on the jet were preliminary vortex generator tests of the five configurations described in the procedures. The results are in table 3 below.

Table 3: Preliminary VG testing

	Low speed	Baseline Low	High speed	Baseline High
Orientation One	17.39	16.655	19.26	17.695
Orientation Two	17.62	16.655	19.63	17.695
Orientation Three	17.46	16.655	19.62	17.695
Orientation Two(bs)*	17.59	16.655	19.78	17.695
Orientation Four(bs)*	16.4	16.655	17.55	17.695
Orientation Five(bs)*	17.77	16.655	19.43	17.695

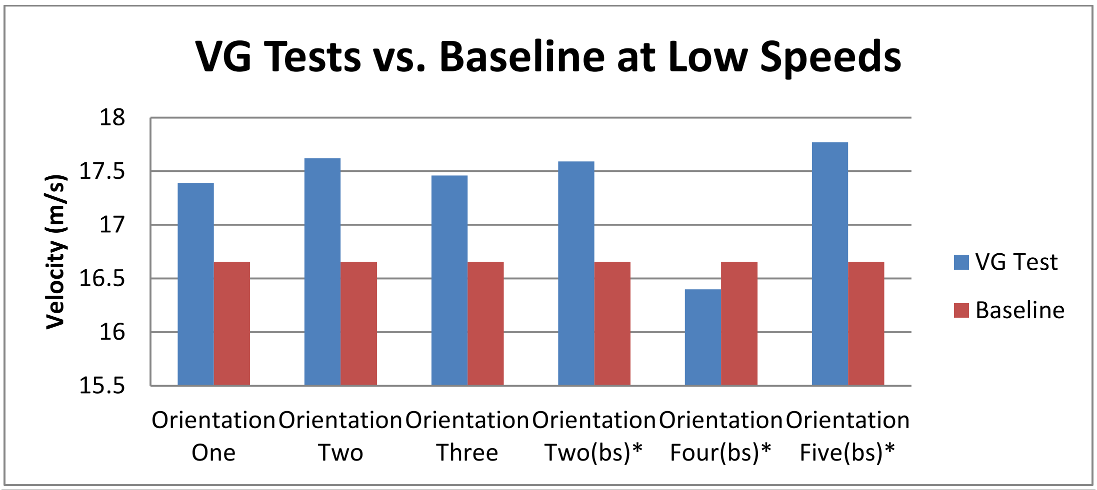


Figure 11: Low speed VG test showing VG5 having the best results, beating even VG2

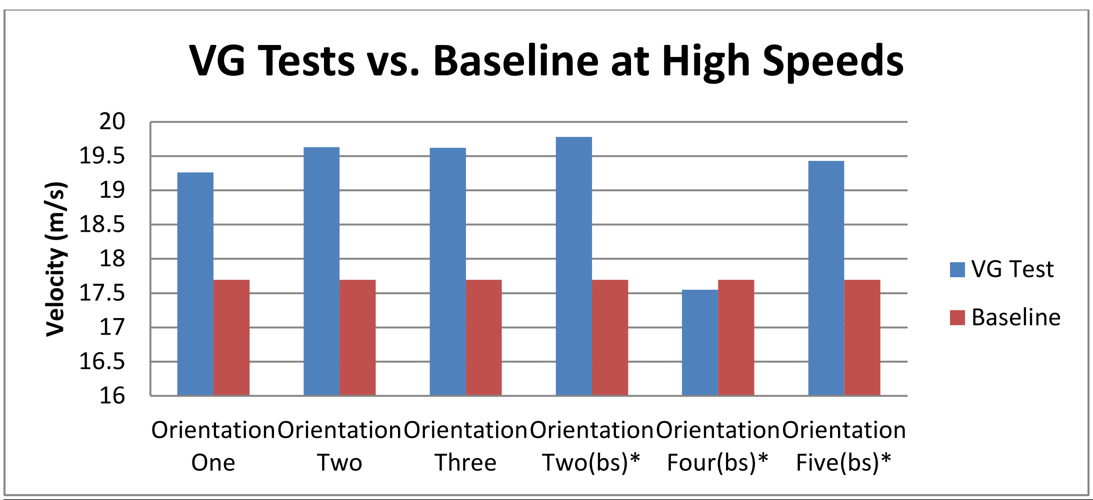


Figure 12: VG 2 preforms the best out of all other configurations tested at high speeds.

The preliminary VG tests were called so because the pitot tubes position inside the outlet of the duct was changed between these tests and all following tests, in order to

conduct the hot wire test for the boundary layer, and therefore are not directly comparable to later tests. The pitot tube was positioned closer to the interior wall of the duct than the following tests. This gave a unique perspective because the flow being sampled in this section is affected more by the viscous and boundary layer effects than later tests where the pitot tube was more centered in the half duct to give more of an overall reading.

As a result of being in the boundary layer affected area the VG's appeared to have an even greater effect on improving air flow. For example VG configuration 2 reduces the loss in air flow by up to 45%. Here the "reduction of loss" term is found in the following manner. Start by taking the difference between the free stream velocity and the base line velocity reading.

$$Free\ Stream\ V - Baseline\ V = 22.31\frac{m}{s} - 17.695\frac{m}{s} = 4.615\ \frac{m}{s}$$

The difference between these two readings represents the loss of air flow in the intake with no modifications, and will be referred to as "base loss". This in turn is compared to "test loss" found in much the same way, except the baseline velocity is replaced with the test velocity. The reduction of loss value is then found by finding what percentage of the base loss is removed by the test loss. Take VG configuration 2 for example:

$$\frac{Base\ Loss - Test\ Loss}{Base\ Loss} * 100 = \left(\frac{4.615 - 2.53}{4.615}\right) * 100 = \left(\frac{2.085}{4.615}\right) * 100 = 45.17\%$$

Even though these results could not be directly compared to later test results, they could be compared among themselves and we were able to take away some valuable information. For example, by comparing the counter-rotating configuration of orientation 1 to the co-rotating configuration of orientation 2 we learned that co-rotating VGs worked better. Both of these orientations were placed at the same location to be directly comparable.

Orientation 3 was tested in order to see the effects of positioning the VG's. It was identical to orientation 2 except it was about twice as far ahead of the inlet. Orientation 3 showed almost identical results to orientation at high speeds but a lower speeds it preformed slightly worse. Based on these results we decided it was of no benefit to move other VG orientations farther ahead of the inlet.

For the next test, orientation 2 was tried again, except this time we put the matching set of VG's on the opposite side of the jet as well. This test was run in order to see if there was any different affects from modifying both inlets as opposed to just the inlet that was being monitored. The difference was minimal but we decided it would be best to continue modifying both side in an attempt to better model real conditions.

Orientation 4 was the first test with vortex generators inside the intake. This test used only 1 VG blade as opposed to the 5 that all other orientations had. This was unintentional but was all we could manage due to the flat surfaces of the vortex generators not sticking to the curved surface of outer wall of the intake. The results of the test showed

that this VG actually made the flow worse than having nothing there at all. Given this effect from such a minor modification we made the assumption that vortex generators on the outer wall were not beneficial.

Orientation 5 was also inside the duct; however it was on the flat inner wall of the intake. It was configured the same as orientation 1, counter-rotating. At low speeds it performed better than any other VGs tested, and at high speeds it was an improvement from orientation 1 but still did not beat the performance of orientation 2. Due to limiting time constraints we had to end the preliminary testing here. Had there been more time we would have tested orientation 2 in the same location inside the duct. Even without that test data, we assumed that the improvement seen between VG 1 and 5 could be applied to VG 2 for even better results.

The final result of the preliminary VG testing was that VG orientation 2 was chosen as the overall best vortex generator design that we had and was selected for further testing. In the future tests orientations two's 5 blade co-rotating design was referred to as configuration 2 regardless of its location.

As mentioned before after the preliminary tests the pitot tube was repositioned closer to the center of the intake duct being tested, this resulted in higher baseline readings. Some other changes with the next tests is that we only tested at the high speed setting in the wind tunnel, 10 volt and 22.31 m/s or 49.9 mph. It was decided that the slow speed setting of 24.95 mph was unnecessary because the jet would not be flying that slow. Another change was in the number of data points collected. We ran 3 quick succession tests averaging the velocities and pressures over 30 seconds as opposed to just 1 test average of 50 second which was done for the VG preliminary tests.

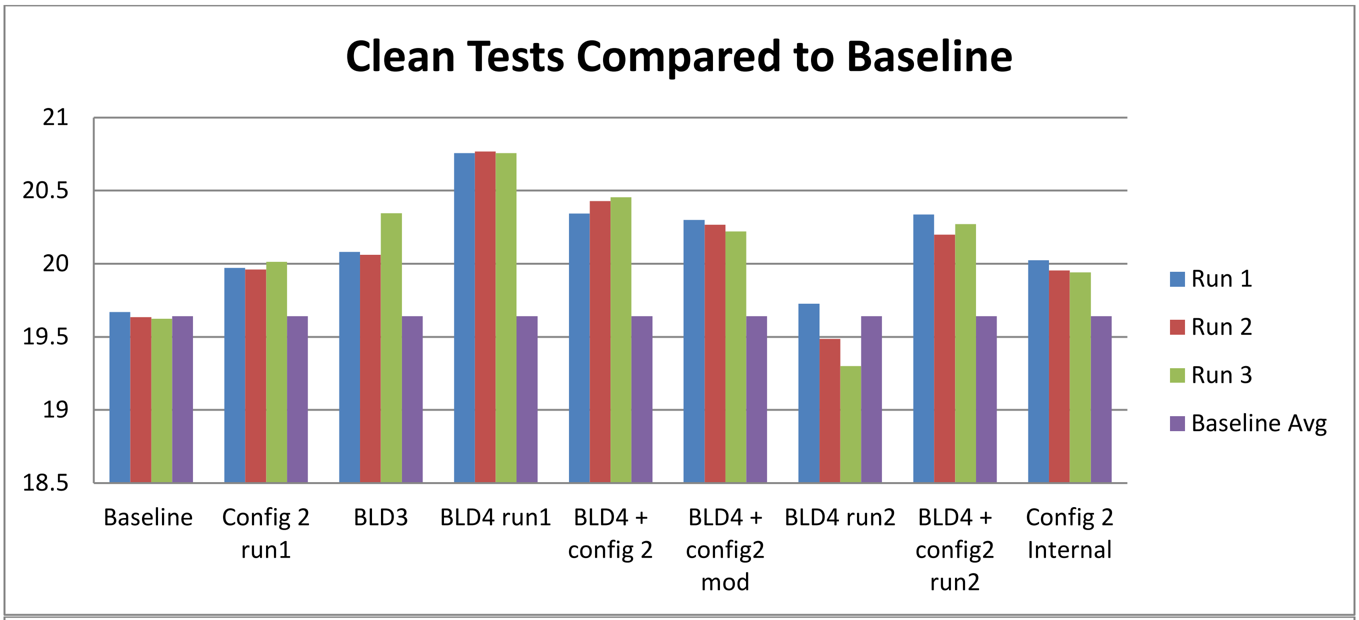
This group of tests was split into two categories called clean and factory.

Table 4

Clean Tests	Run 1	Run 2	Run 3	Average
Baseline	19.67	19.64	19.62	19.64
Configuration 2	19.97	19.96	20.01	19.98
BLD3	20.08	20.06	20.35	20.16
BLD4 run1	20.76	20.77	20.76	20.76
BLD4 + config. 2	20.34	20.43	20.45	20.41
BLD4 + config2 mod	20.30	20.27	20.22	20.26
BLD4 run2	19.73	19.49	19.30	19.50
BLD4 + config2 run2	20.34	20.20	20.27	20.27
Config 2 Internal	20.02	19.95	19.94	19.97
Factory Tests				
Baseline	19.36	19.35	19.30	19.34
BLD1	19.51	19.53	19.61	19.55
BLD2	18.70	18.62	18.68	18.67
Config 2	20.15	20.08	20.06	20.10
Config 2 + Counter rotating	19.10	19.01	19.02	19.04
Config 2 internal	19.75	19.73	19.67	19.72

Clean tests mean that the small gap where the intake duct connects to the frame of the jet has been seal off using tape, as shown in the figure 13. This had already been done to some of the jets in use by the flight team with positive results of up to 10% increase in thrust efficiency. Factory tests on the other hand refer to tests that were run with the intake just as it would be straight from the factory, therefore no tape. The data from table above are represented in the graphs below.

Figure 13: "Clean" Baseline



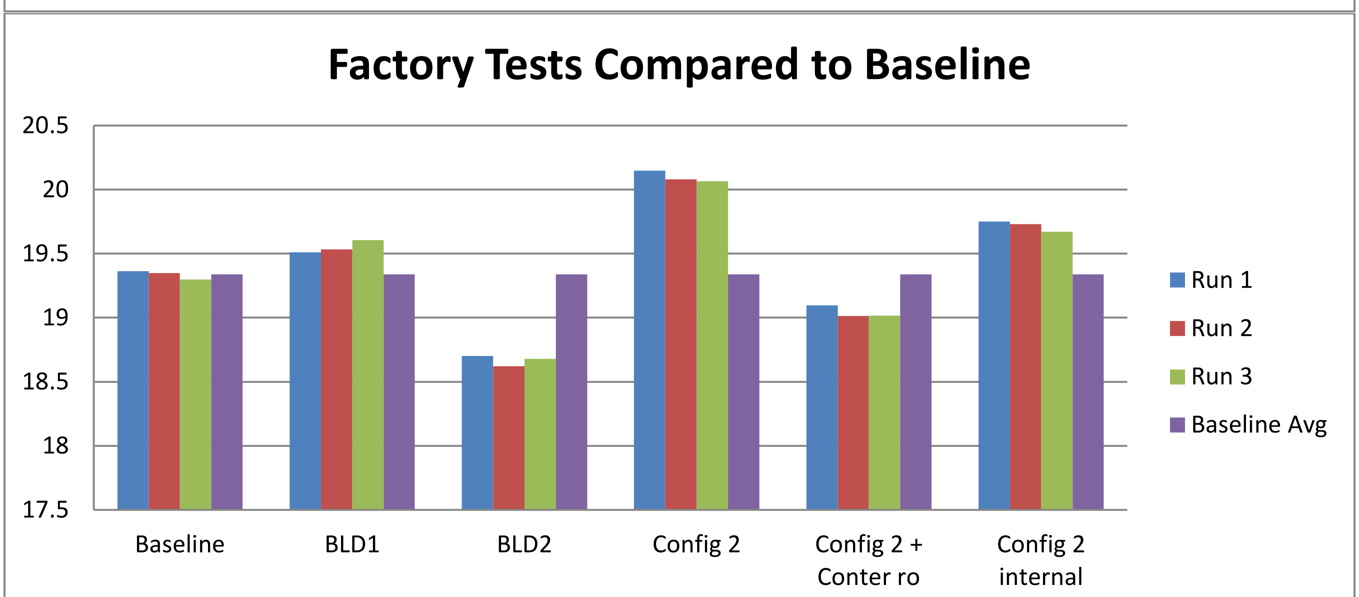


Figure 14: All collected data from both clean and factory tests compared to the average baseline

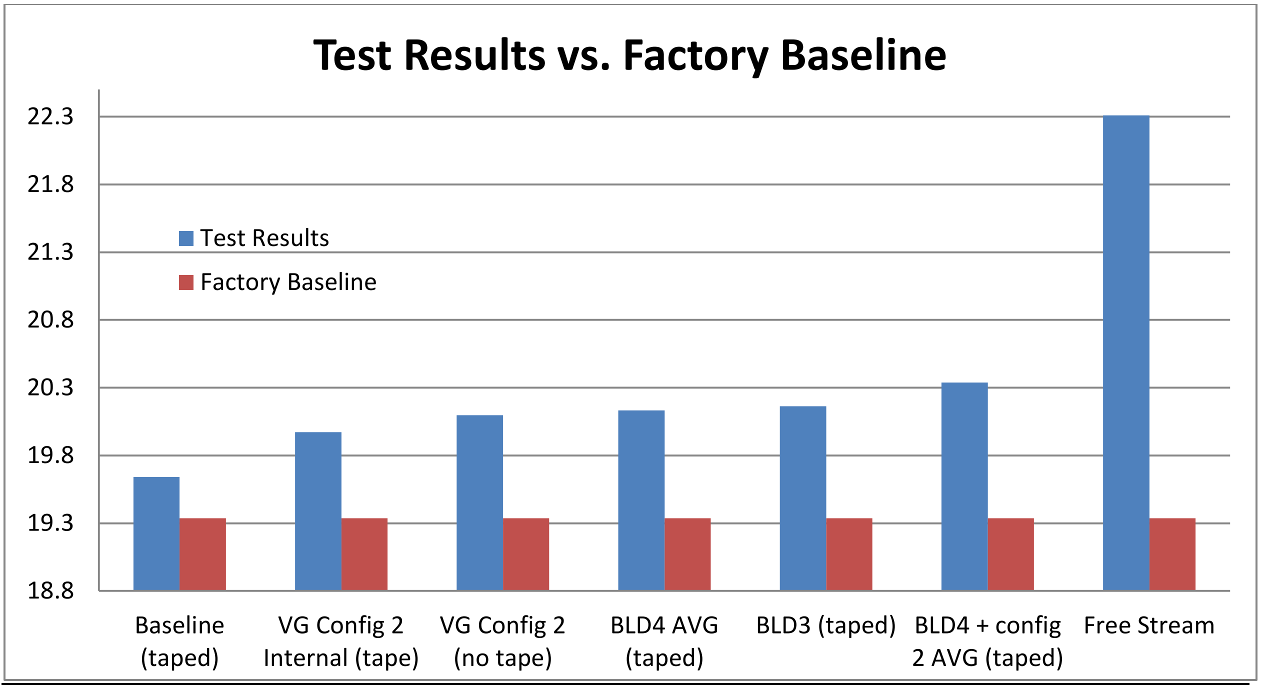


Figure 15: Reduced data set showing some of the better results compared to the factory baseline.

From the graphs on the previous page it would appear as if BLD 4 performed the best. While it did show the best velocity improvement of 20.76m/s in its first test run, we re-ran that test with extremely contrasting results of 19.5m/s. The low reading is even worse than the clean baseline of 19.64. However the clean tests were run in the order that they appear in both table 14. As you can see from those orders the low reading of the BLD 4 was chosen after BLD 4 had already been picked as the best to be combined with VG configuration 2. The BLD4 VG2 combination had the second best results behind only the high reading of BLD 4 as a standalone item. We still chose the BLD4 VG2 combination as the best based on the results of its second test. While the BLD 4 performed much worse the combined set up had very consistent results.

The graph in figure 15 at the top of the page shows some of the top results in order. Notice that the BLD 4 and the BLD4+VG2 are the average results from their two tests. The test results are compared to the factory baseline as well as the free stream velocity on the far right in order to better visualize the reduction of losses. The base loss would be the difference between the free stream velocity and the factory baseline velocity. The percent reduction of loss can be found by dividing the difference between each test velocity and the factory baseline velocity, then dividing that value by the base loss. The factory baseline used instead of the clean baseline because adding the tape improves the flow on its own and we wanted to measure total improvement.

Table 5: All Test Items Ranked in Order of Improvement

Rank	Test	Duct Outlet Velocity (m/s)	% Reduction of loss
1	BLD4 + config 2 AVG (C)	20.34	33.70
2	BLD4 + config2 mod (C)	20.26	31.11
3	BLD3 (C)	20.16	27.79
4	BLD4 AVG (C)	20.13	26.75
5	VG Config 2 (F)	20.10	25.55
6	VG Config 2 (C)	19.98	21.70
7	VG Config 2 Internal (C)	19.97	21.38
8	VG Config 2 internal (F)	19.72	12.77
9	Baseline (C))	19.64	10.27
10	BLD1 (F)	19.55	7.14
11	Baseline (F)	19.34	0.00
12	Config 2 + Conter ro (F)	19.04	-9.93
13	BLD2 (F)	18.67	-22.54

So far most discussion on these tests have involved the top results. Now let's focus on some of the less effective items and investigate what went wrong. Starting with the worst, what was the problem with BLD 2? It had the same top face as BLD 1 and 3, what was different? All three had different wedges separating them from the surface of the jet. The wedge used in BLD had a curved geometry, however that shouldn't have had such a huge negative effect, in fact at the speeds we were testing at it should have reduced drag. That leaves the height, the height of BLD 2 was measured to be 10.5mm from the jet. BLD 2 might have had much different results had the boundary layer actually been as large as we initially assumed, but with the boundary layer being closer to 6mm this boundary layer diverter was likely causing more drag and blockage than it was removing. Much the same can be said for BLD 1, which had a height of 7.5mm and resulted in only the slightest improvements. BLD 3 and 4 had heights of only 6mm and had remarkably improved performance.

The second worst results occurred when we took configuration 2 which had had been consistently causing a 20% reduction of loss and then added a counter rotating vortex generator to the outer wall of the inlet duct. This had been tried before with poor results in preliminary testing but we wanted to try again to confirm the negative effects of VGs on that wall; negative effect confirmed.

Configuration 2 was tested multiple more times and continued to produce good results. However BLD 3 and 4 had better individual results but combined for the best results.

After conducting all the tests it was realized that in order to quantify the efficiency of the ducting both the dynamic and stagnation pressures were needed and we had only recorded the dynamic. As a result we conducted a follow on test to find the relationship between dynamic pressure which was known and the stagnation pressure. Using the same leaf blower as before and ducting the same size as the ducting used during the main test we tried to map out the pressure relationship for a series of flow resistances.

By setting the blower to high, just as before and testing a variety of resistances the following relationship was found.

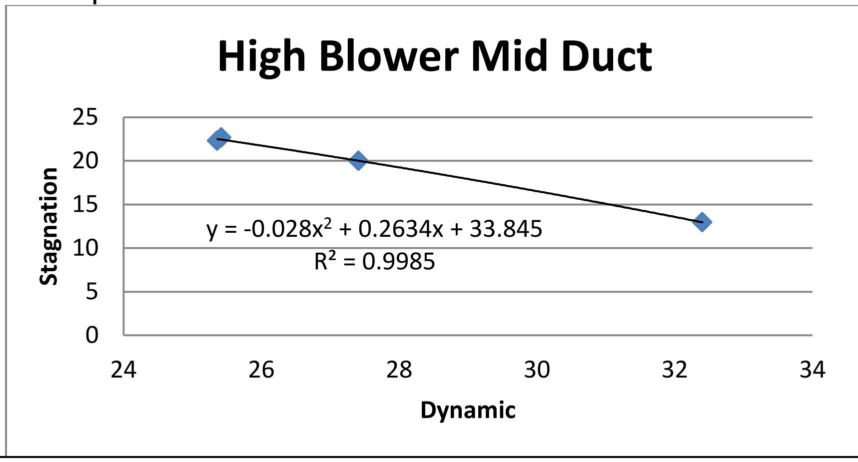


Figure 16: Relationship of dynamic and stagnation pressure in the testing duct.

The equation from the polynomial trend line was used to along with the dynamic pressures found in the main test in order to find their matching stagnation (total) pressures. Next due to the lack of an actual efficiency equation another qualifying term had to be used, in this case we choose to use the loss coefficient which is equal to the difference total pressure divided by the dynamic pressure. The loss coefficient of the factory baseline was then compared to the loss coefficient to find a percent change from some of our tests. Those results can be seen in table 6 below.

Table 6: Pressure loss coefficient and % change

Configuration	Loss coefficient	percent change
Factory baseline	1.087	0.00
Taped baseline	1.021	6.11
VG 2	0.954	12.26
BLD 4	0.922	15.24
BLD 4+ VG 2	0.883	18.77

5 CONCLUSIONS & RECOMMENDATIONS

In conclusion after conducting a series of a comparative wind tunnel test we found that the combination of a square leading edge boundary layer diverter with a height of 6mm followed by 5 co-rotating vortex generators in the duct produced the best results. They reduced the loss of velocity in the outlet of the intake ducts by an average of 33%. While it is unknown exactly how much this increase in velocity will increase thrust output in the BVM jet it can be assumed that it will be closer to the uninstalled thrust output than before. As a comparison, thrust tests have been run with an assembled BVM jet that had the small gaps at the inlet taped like in our “clean” tests and showed a 10% increase in thrust. It may just be a coincident but the reduction of loss velocity in our clean baseline test was also 10%. If the thrust loss and velocity loss are directly correlated to one another then we may be able to reduce up to a third of the losses.

However it would be my recommendation that prior to permanently attaching the boundary layer diverter and vortex generators to the jet that some more tests be conducted. We tested a fair range of configurations but there are an unlimited number of possibilities. What we learned from these tests is that by applying BLDs and VGs airflow can be improved. If our results were taken as is and applied to the jet there should be thrust increase, however these results have not been truly optimized.

What we found in our test is what generally worked well. For the best results I would suggest taking what we learned in this test and expanding on it, trying small variations. For example, while testing boundary layer diverters we had our best results with a height of 6 millimeters which is approximately the same height as the boundary layer according to the hot wire test. We tested larger heights of 7.5mm and 10mm but none smaller. It may be beneficial to see the effects of reducing the height to perhaps 5 or even 4mm. That is a very small change but if you look at the results of BLD1 compared to BLD3 & 4 there is only a 1.5mm difference in height but a fairly large difference in air flow. Another consideration on the BLD’s is that the geometry used as the diverter. On BLD 1, 3, and 4 the diverter was a simple triangle. It could be beneficial to see the effects of changing this geometry. We had tried a curved geometry with BLD 2 however the effects of that geometry were lost due to it having a height of 10mm. Trying that test again at a lesser height could show some improvement due to a curved edge being more aerodynamically sound at subsonic speeds than a pointed edge. The last note I have on BLDs is that even though we had our best results with the square leading edge BLD 4, we also had some of our worst. Due to the inconsistent nature of these test results, in future tests I would suggest using both the square leading edge and the parallelogram BLD until more concrete results can be obtained.

VG configuration 2 did show consistent improvement to the air flow, but there could still be some better options that we did not test. Looking back at the VG preliminary test results you can see that orientation 2 actually didn’t have the best results at lower speeds, orientation 5 did. Orientation 5 was a counter-rotating VG identical to orientation 1, except that it was positioned inside the intake. It was simply assumed due

to lack of time for additional tests that a co-rotating VG would perform better inside the duct just as configuration 2 outperformed orientation 1just outside the duct. However in the next set of tests, VG 2 was tested both in front of and inside of the inlet, and preformed slightly worse inside the duct. That being said, our previous assumption that VG2 will do better than VG 5 could have been wrong, because the anticipated improvements were not seen. Therefore I would recommend retesting VG5 in a direct comparison to VG2 in the duct. I would not be surprised to see VG5 perform better, making it the better choice for being combined with a BLD. A final note on the VGs, is that all my designs were based on the blades being set at a 20 degree angle more or less (manufacturing errors). That is on the high end of what other research has used, which normally ranges from 12 to 20 degrees, therefore if additional tests are run, it would be wise to observe the effect of lowering the angle of attack for the VG blades.

Here are a few manufacture notes that may be helpful in making the final product. Firstly, we found that galvanized steel sheet worked much better than aluminum sheet metal, it was much better at handling the 90° bends. The aluminum sheet was too hard and would break to stress fractures along the bend. With the boundary layer diverters we used 2 ply carbon fiber and were very happy with the results. It was very thin yet strong, and it could still bend to the contour of the jets surface. For the diverter itself though we used foam because it was not meant to permanent, therefore a different material should be used for that. One possible solution could be to just adding a one or two ply skin to a foam cut out similar to the test item, only thinner to compensate for the added thickness of the carbon fiber. The carbon fiber/foam composite would be both strong and light weight.

6 APPENDIX

Preliminary VG test data

Baseline - NO VG's						
	Test1		Test 2		Average	
Setting	Velocity	Pressure	Velocity	Pressure	Velocity	Pressure
Tun Low	16.81	17.27	16.5	16.64	16.655	16.955
Tun High	17.79	19.36	17.6	18.98	17.695	19.17
No Air	14.88	13.52	14.76	13.35	14.82	13.435

	Low speed	Baseline Low	High speed	Baseline high	high test loss	% reduction of loss
Orientation One	17.39	16.655	19.26	17.695	3.05	33.91115926
Orientation Two	17.62	16.655	19.63	17.695	2.68	41.92849404
Orientation Three	17.46	16.655	19.62	17.695	2.69	41.71180932
Orientation Two(bs)*	17.59	16.655	19.78	17.695	2.53	45.1787649
Orientation Four(bs)*	16.4	16.655	17.55	17.695	4.76	-3.141928494
Orientation Five(bs)*	17.77	16.655	19.43	17.695	2.88	37.59479957

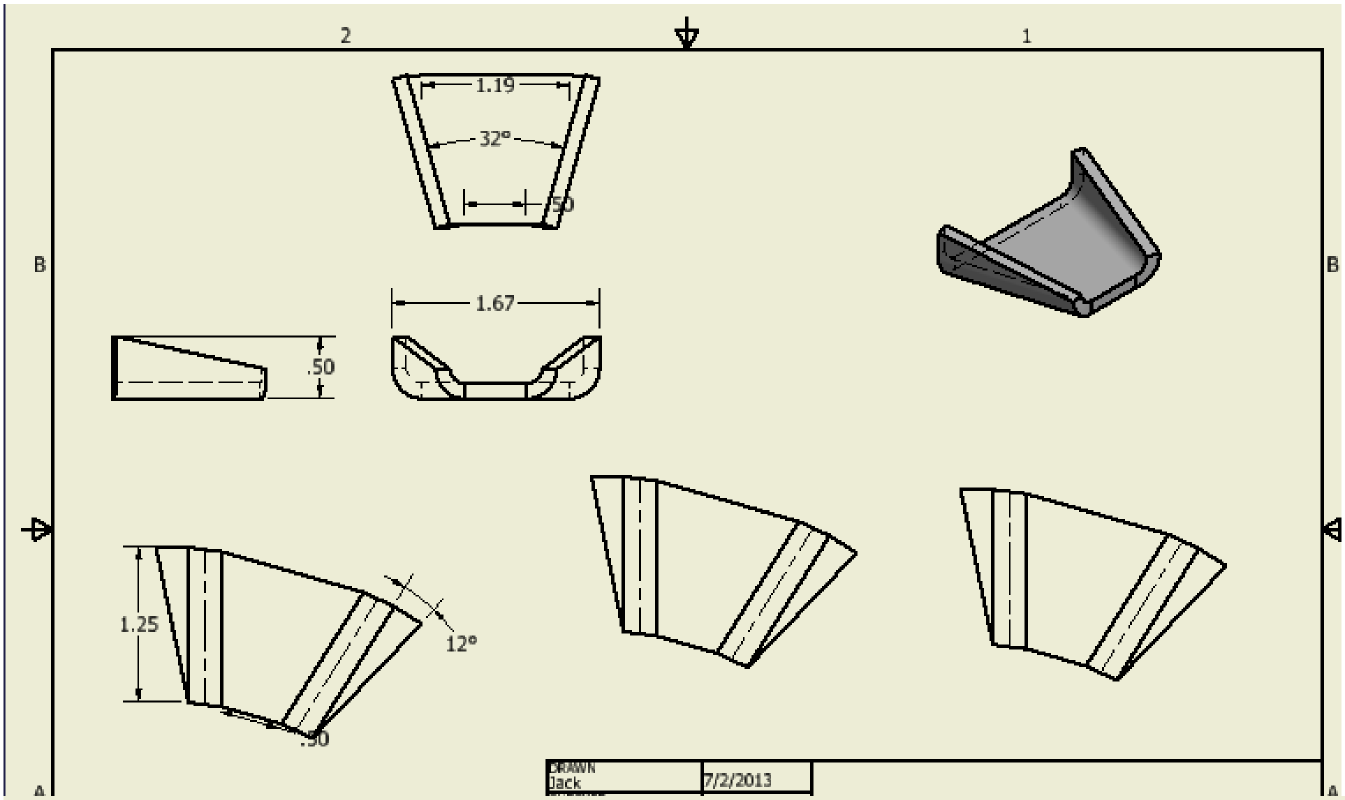
Main test raw data

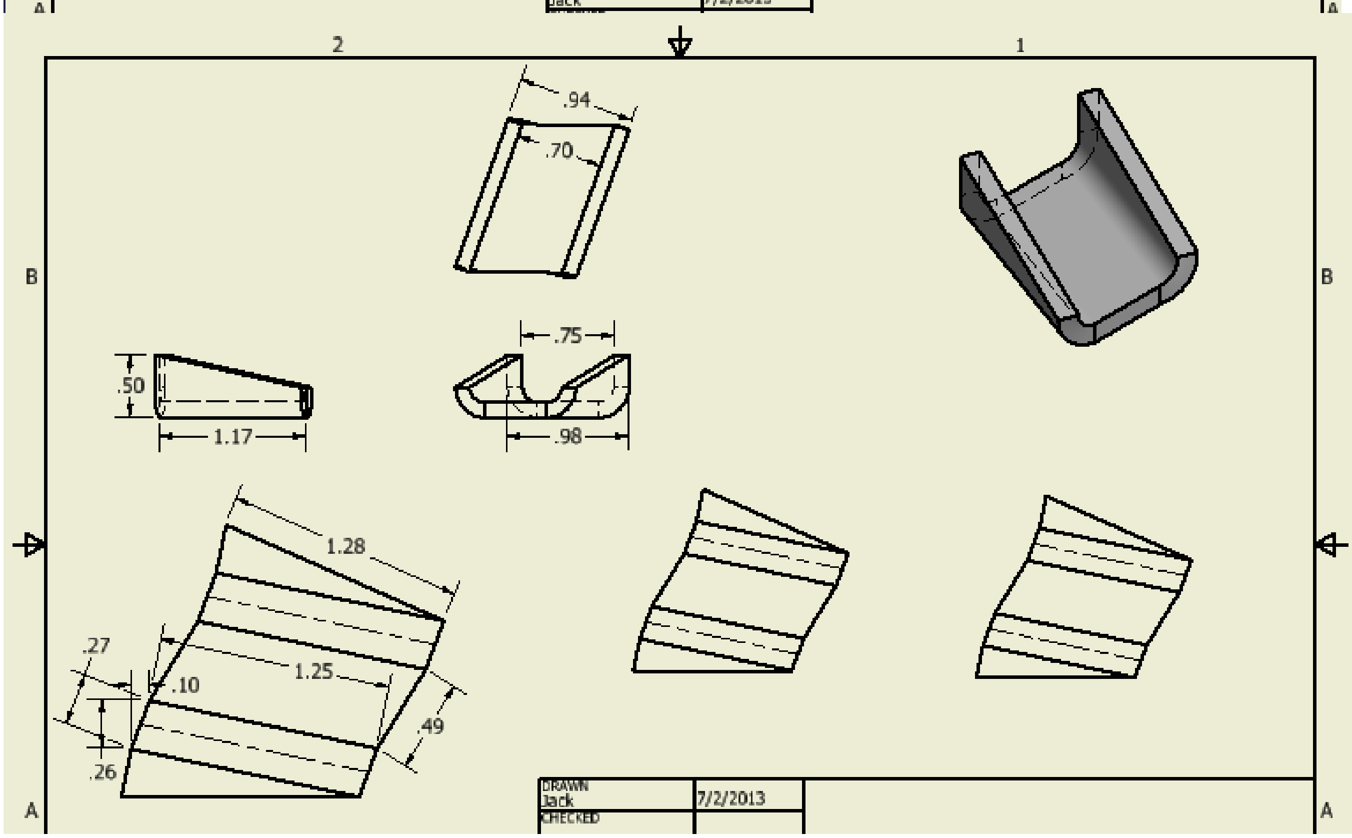
Configuration 2 (#2)Clean	1	2	3
V	19.972	19.96	20.014
P	24.24	24.29	24.38
Configuration 2 (#2) Factory	1	2	3
V	20.146	20.08	20.064
P	24.73	24.58	24.51
BLD1 Factory	1	2	3
V	19.511	19.532	19.605
P	21.17	23.38	23.38
BLD2 Factory (curved)	1	2	3
V	18.701	18.622	18.678
P	21.31	21.13	21.26
Clean Baseline (#2)	1	2	3
Velocity(m/s)	19.669	19.635	19.623
Pressure(mmH20)	23.64	23.54	23.48
Baseline Factiory	1	2	3
V	19.364	19.349	19.298
P	22.85	22.78	22.74
Configuration 2 + Counter-rotating VG	1	2	3
V	19.095	19.014	19.016
P	22.22	22.03	22.02
VG Configuration 2 (3 inside duct) no tape	1	2	3
V	19.749	19.73	19.671
P	23.78	23.7	23.54
BLD3 (Clean)	1	2	3
V	20.082	20.062	20.346
P	24.52	24.53	25.2
BLD4 (Clean)	1	2	3
V	20.756	20.767	20.756
P	26.26	26.3	26.26
BLD4 + Configuration 2	1	2	3
V	20.344	20.429	20.454
P	25.2	25.34	25.44
BLD4 + Modified Configuration 2 (Clean)	1	2	3
V	23.782	24.323	24.397
P	34.5	36	36.26
RERUN of Previous setup	1	2	3
V	20.299	20.267	20.22
P	25.06	24.96	24.9
RERUN of BLD4 (Clean)*	1	2	3
V	19.726	19.487	19.301
P	23.7	23.1	22.68
RERUN of BLD4 + Configuration 2	1	2	3
V	20.336	20.199	20.271
P	25.19	24.88	24.94

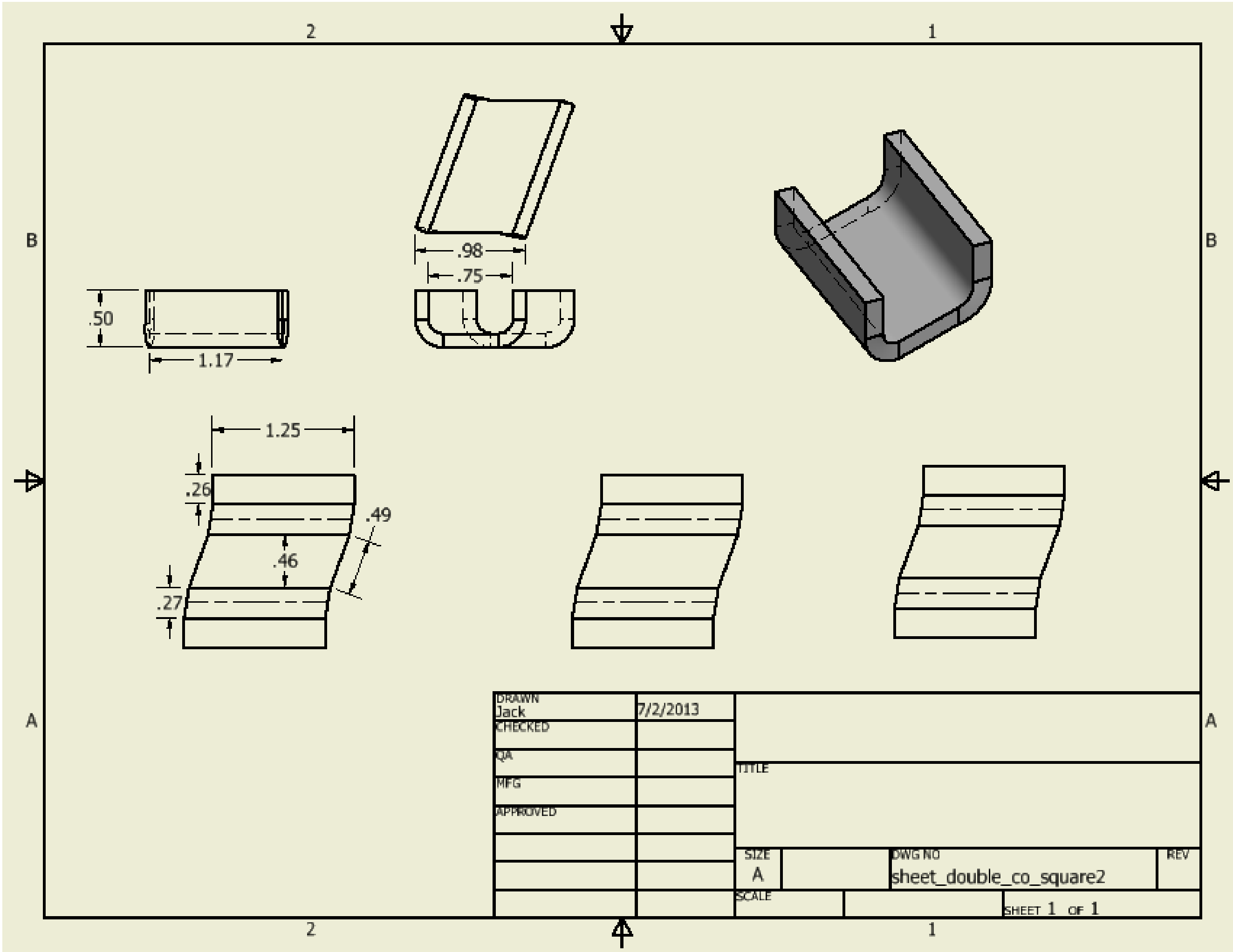
Follow on test data

High Blower middle duct				Low Blower middle duct		
Tube Length"	Dynamic	Stagnation	Static	Dynamic	Stagnation	Static
15	29.29	1.18	30.37	19.67	1	20.7
33	32.4	12.96	45.4	21.97	8.89	30.9
51	27.41	20	47.89	19.47	13.23	33.13
69	25.42	22.65	47.77	17.56	15.3	32.49
87	25.36	22.29	47.19	17.67	15.1	32.19
High Blower free stream				**Low Blower free stream**		
Tube Length"	Dynamic	Stagnation	Static	Dynamic	Stagnation	Static
15	21.93	0	22.38	21.93	-0.01	22.38
33	20.24	0	20.21	13.78	0	13.88
51	15.48	0.05	15.68	10.68	0.03	10.75
69	16	0.13	16.11	11	0.07	11
87	14.71	0.023	14.91	10.05	0.15	10.15

VG Inventor Drawings



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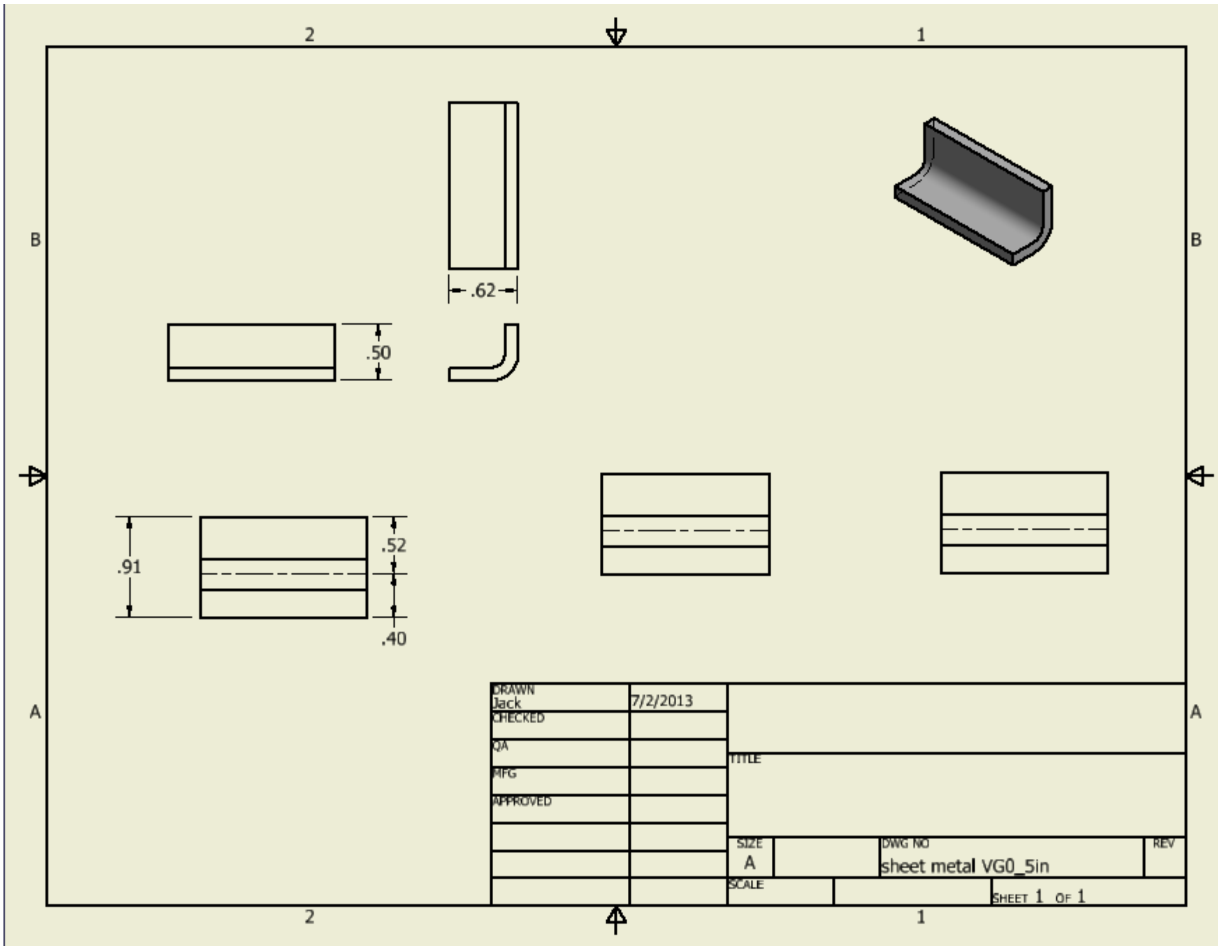
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